TECHNICAL REPORT

FIELD TESTING OF A PROTOTYPE HEAT STRESS MONITOR: SYSTEM PERFORMANCE AND APPLICABILITY TO COMMERCIAL MINING IN AUSTRALIA

FINAL REPORT FOR CRDA No. 9503-M-C582 (DAMD17-95-0060)

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13. ABSTRACT *(Maximum 200 words)*
Under a Cooperative Research and Development Agreement (CRDA), a prototype environmental Heat Stress Monitor (HSM) originally developed for military use, was evaluated for potential applications as a heat stress management tool in the Australian mining industry. The hand-held electronic HSM combines a thermal strain prediction model with an integrated environmental sensor suite that measures air temperature, humidity, wind speed, and solar radiation, to provide tailored guidance on hourly drinking water needs, optimal work/rest cycle limits, and maximum safe work time. Overall system performance of three prototype HSMs was evaluated at a commercial oil production facility at Barrow Island, Australia, and a single prototype was evaluated for potential use in deep copper mine environments in Queensland, Australia. Results at Barrow Island indicated that although conceptually suitable for use in those outdoor environments, additional engineering work on the HSM wind speed sensor is needed to bring that sensor within required accuracy tolerances. The deep mine evaluations identified additional system requirements that would be essential for acceptance in that production environment. These included a back-lighted liquid crystal display, autonomous data logging capability, additional program space, and computer interface support for calibration services and data download. Based on the magnitude of these system enhancements and our need to satisfy stated military requirements for a smaller/lighter device, we have concluded that a major redesign of HSM is appropriate. We recommend that a new prototype HSM with strong dual-use applicability be developed and tested in laboratory and field environments.

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EXECUTIVE SUMMARY

This report describes the results of field evaluations of prototype environmental Heat Stress Monitors (HSMs) in both outdoor and deep mine industrial settings in Australia. The pocket-sized HSMs employ microprocessor technology to integrate a comprehensive thermal strain prediction model with automated, real-time measurements of air temperature, relative humidity, wind speed, and solar load. Based on user specified activity level, clothing type, and acclimatization status, the HSM automatically computes and displays optimal work/rest cycle limits and hourly drinking water needs. The HSM can also display prevailing air temperature, black globe temperature, mean radiant temperature, wet bulb temperature, Wet Bulb Globe Temperature (WBGT), wind speed, and relative humidity in either metric or English units

This effort was undertaken as part of a Cooperative Research and Development Agreement (CRDA) between the U.S. Army Research Institute of Environmental Medicine and the School of Public Health, Curtin University of Technology, Perth, Western Australia. The overall objective of the CRDA is to identify design requirements for an environmental Heat Stress Monitor that is suitable for use as a heat stress management tool for workers in the petroleum and mining industries in Australia. The specific objectives of these tests were to evaluate the accuracy of the current HSM sensor suite, verify the predictive model implementation, and identify any design changes that would improve suitability and marketability of the HSM for application in these industrial settings.

Outdoor testing was conducted at an oil production facility operated by West Australia Proprietary Limited (Wapet) on Barrow Island, Western Australia, in January 1995. The mine application study was conducted in a deep (1700 meters below MSL) copper mine operated by Mt. Isa Mines Limited, Queensland Australia, in July 1995.

Results of the sensor performance evaluations indicated that accuracy of the air temperature and humidity sensors was adequate but improvements to the wind speed and black globe sensors were needed. Wind speed sensor errors were found to be related to stem effects and engineering corrections have been planned to correct these deficiencies.

Specific design requirements have been identified and the scale of these modifications suggests an extensive re-design of the HSM for industrial applications in Australia. Additional requirements include increased memory space for program and data storage, a data-logging and computer download capability, calibration facilities, and the addition of a barometric pressure sensor. Consolidation of these requirements with Army requirements for a smaller and lighter physical unit could provide development cost efficiencies for dual use.

2. INTRODUCTION

HEAT STRESS MONITORING. The evolution of strategies to manage heat injury risk in military and industrial settings has focused on the idea that if the prevailing heat stress can be adequately quantified, then appropriate counter measures can be implemented to minimize thermal strain. This philosophy is reflected in current military heat injury prevention procedures (TB Med 507, 1980; GTA 8-5-45, 1985; FM 21-10, 1988) and also in civilian programs intended to reduce heat injuries in industrial settings (NIOSH, 1986). Although physiological heat strain, and the potential for heat injury, are determined to a great extent by the prevailing environmental conditions, the individual's clothing characteristics, acclimatization status, and activity level also play critical roles. The capability to account for the complex interactions of these variables in dynamic environments where workers must function safely at or near their physiological limits requires the integration of reliable sensors and predictive model technologies in a lightweight, rugged, package.

CURRENT SYSTEMS. Existing heat stress monitoring approaches are based largely on the Wet Bulb Globe Temperature (WBGT) and the related Wet Globe Thermometer (WGT). These systems provide the user with a single temperature, or index, which in conjunction with appropriate look-up tables or charts may be used to determine heat injury risk categories and recommended work limits and water needs. The inherent limitations of the WBGT and WGT in terms of applicability across a broad range of potential military and industrial applications have been reported (Gonzalez et al., 1985; Matthew et al., 1986, 1987; Tilley et al., 1987). These limitations can be attributed in part to early constraints on sensor and computational complexity (Yaglou and Minard, 1957) but a more fundamental limitation is the conceptual basis itself: WBGT and WGT are exclusively environmental and do not directly evaluate strain potential in the context of clothing and metabolic factors.

MERGED HEAT STRESS MONITOR/CALCULATOR CONCEPT. Mathematical models of human heat strain allow full consideration of the complex interactions of environment, clothing, acclimatization status, and metabolic heat production that ultimately determine human performance limits for a given physical task. Although some predictive models are computationally very intensive, USARIEM has developed and implemented a heat strain prediction model that runs on a Hewlett-Packard 41 CV hand held calculator (Pandolf et al., 1986). The calculator provides tailored guidance on maximum safe work time, optimal work/rest cycle limits, and hourly drinking water needs. Although very portable itself, the calculator requires the availability of measured data for the environmental inputs: air temperature, humidity, wind speed, and solar radiation. In early 1990, USARIEM proposed consideration of a heat stress monitoring device that would integrate an environmental sensor suite with the calculator's heat strain prediction model software. The approach takes advantage of advances in sensor, display, and

microprocessor technologies to enable direct read-out of work/rest cycle limits and hourly water requirements based on specified clothing and work rate scenarios. The physical implementation of the merged monitor/calculator concept is currently known as the environmental Heat Stress Monitor (HSM).

HEAT STRESS MONITOR PROTOTYPES. Rugged, pocket-sized prototype environmental Heat Stress Monitors (HSMs) have been developed. The materiel developer was the U.S. Army Medical Materiel Development Activity (USAMMDA), Fort Detrick, Frederick, Maryland. Three HSM prototypes, built by Southwest Research Institute (SwRI), San Antonio, Texas, were delivered to USARIEM in November 1992. Technical specifications are listed in Table 1. The microprocessor-based HSM integrates the USARIEM heat strain prediction model with a sensor system that provides automatic measurement of the needed environmental heat stress parameters. The user selects inputs for clothing type, work load, and acclimatization status using five function keys and a simplified menu shown on the HSM's Liquid Crystal Display (LCD). After a three minute measurement period, the HSM displays the tailored guidance for optimal work/rest cycle limits and hourly drinking water needs. Measured air temperature, wind speed, relative humidity, and black globe temperature as well as computed mean radiant temperature and Wet Bulb Globe Temperature (WBGT) index may also be viewed by the user in either English or metric units.

Table 1. Overview of HSM prototype characteristics and specifications.

A. CHARACTERISTICS: Size: 14 x 4.4 x 9.7 cm (5.5 x 1.75 x 3.8 in) Weight: 0.68 kg (1.5 lb)			
B. USER INPUT: 5 keys - 2 menu scroll keys and 3 "soft" entry keys			
C. OUTPUT DISPLAY: Liquid Crystal Display (LCD), 4 lines x 20 characters			
D. SENSOR SYSTEM PERFORMANCE SPECIFICATIONS:			
Parameter	Sensor type	Accuracy	Range
Air Temperature	Thermistor	±0.6 °C	5 - 65 °C
Relative Humidity	Capacitive	±4.5 % RH	0 - 100 % RH
Wind Speed	Heated Thermistor	±0.5 m/s ± 10 %	0.5 - 4.5 m/s 4.6 - 6.7 m/s
Globe Temperature	1.9 cm dia. Globe	±0.6 °C	5 - 77 °C

HSM PROJECT STATUS. Results of laboratory wind tunnel testing at USARIEM in 1993 indicated that overall performance of the prototype HSM as a integrated system was good, but modest additional effort was needed to improve sensor calibration and correct minor software problems (Matthew et al.,

1993). These modifications were completed in 1994 at about the time the Army Medical Department (AMEDD) combat developer determined that the HSM would no longer be considered a medical item. This terminated funding support for the final phase of HSM development. USARIEM therefore sought an interested partner to assist in completion of the outdoor test phase and to pursue final development of a production HSM.

HSM DEVELOPMENT PARTNERSHIP. This study was planned and conducted as a partnership effort between USARIEM and the School of Public Health, Curtin University of Technology, Perth, Western Australia under a 1995 Cooperative Research and Development Agreement (CRDA, Control No. 9503-M-C582, U.S. Army Medical Research and Materiel Command reference No. DAMD17-95-0060). The overall objective of this CRDA was to identify design requirements for a production HSM that would be suitable as a heat stress management tool for the petroleum and mining industries in Australia.

OBJECTIVES AND SCOPE OF EFFORT

OBJECTIVES. This work was intended to accomplish the following objectives:

1. Determine the accuracy of the HSM's air temperature, relative humidity, black globe, and wind speed sensors across the daytime range of a hot natural outdoor environment and also at discrete locations in a deep mine environment.

2. Verify the HSM's Heat Strain Model implementation.

3. Evaluate the applicability of HSM predictive model outputs in the context of production oriented surface and deep mine industrial operations.

SCOPE OF EFFORT. Scope is limited to a field assessment of HSM system function by the USARIEM team. There was no real-time utilization of HSM output to modify the behavior of workers during either the outdoor or deep mine evaluations. The contemporary physiological data collection effort by the Curtin University team during outdoor testing was accomplished under the Curtin team's local human use/ethics approval authorities and is reported in detail elsewhere (Gazey et al., 1996).

METHODS

PRE-TEST CHECKS AT USARIEM. Prior to the field tests, we conducted limited calibration checks on the prototype HSMs and the portable weather station that would provide the basis for evaluating HSM sensor performance in the field. Each HSM completed 3 measurement cycles in each of 4 test environments at a constant 50% RH: Air temperatures of 25 and 35 ^{o}C, and wind speeds of 1.0 and 2.5 m/s.

TEST LOCATIONS. The outdoor study was conducted at Barrow Island, Western Australia in late January 1995. The deep mine survey study was conducted at Mount Isa Mines Limited facilities in Queensland in July 1995.

<u>Barrow Island</u>. Barrow Island lies 1,300 km north of Perth and 56 km from the mainland of north-western Australia. The Island is about 25 km long and 10 km wide with a total land area of 234 km^2. Barrow Island is considered to be one of the most important wildlife reserves in Australia and, through the conscientious application of rigorous environmental protection controls, also supports an active oil production facility operated by West Australia Petroleum Proprietary Limited (Wapet). Workers at this facility work 10 to 12 hour shifts in daytime temperatures that frequently exceed 40 ^{o}C, and the prevention of heat injury is an important management concern. This location afforded an opportunity to evaluate HSM system performance in the context of a relevant occupational task environment. Some of the physiological measurements and all of the meteorological and HSM sensor data were obtained at well No. E16 work site. Additional contemporary physiological measurements were obtained at nearby work sites.

<u>Mount Isa Mines</u>. Mt. Isa is located 780 km west of Townsville in Queensland Australia and employs a total of approximately 3,500 workers in both underground and above ground operations. The mine produces copper, lead, silver, and zinc from 19 shafts that extend to depths approaching 1800 meters. The total length of underground openings at Mt. Isa Mines is approximately 500 km. The presence of ground water seeps and the use of water sprays to control dust in locations where exposed rock temperatures exceed 50 ^{o}C can result in very high temperature and humidity conditions. The underground environments provided an opportunity to evaluate the HSM performance in the context of Mt. Isa's heat injury prevention program that is based primarily on the cooling power index derived from measurements of air temperature, wet bulb temperature, and air movement.

ENVIRONMENTAL MEASUREMENT INSTRUMENTATION. At Barrow Island, reference measurements of the local outdoor environment, consisting of one minute interval wind speed, relative humidity, air temperature, and black globe temperature data were obtained using a Campbell model CR-10 portable

weather station. A 3-minute HSM measurement cycle was initiated at the beginning and at 30 minute intervals throughout the test day. In the deep mine environments, Mt. Isa Mines corporate Occupational Health personnel made all reference environmental measurements using their standard equipment sets. These consisted of an accumulating wind vane anemometer, an integrated electronic hot wire anemometer, air temperature and humidity read out device (Kanomax Climaster, model 6511), a Reuter-Stokes mini-Wibget electronic WBGT meter, and a sling psychrometer. At selected workplace locations deep in the mine, during the 3-minute HSM measurement cycle, Mt. Isa staff called out and recorded their instrument readings. The HSM measurement start time and all output values were manually recorded. Sensor performance was assessed by comparison with the appropriate 3 minute average values for the time-indexed weather station or reference instrument data.

Black Globe Sensor. The HSM employs a bead thermistor inside a miniaturized 1.9 cm diameter black globe sensor to assess the solar load. Because a globe size correction algorithm (Peters, 1976), which employs the wind speed and air temperature measurements, is implemented in the HSM, the output value should be equivalent to that of a full size, 15 cm diameter, black globe.

Air Temperature and Humidity Sensors. The HSM uses a bead thermistor for air temperature and the HyCal model IH-3602 monolithic sensor for humidity. The HSM air temperature and humidity measurements should be equivalent to standard meteorological measurements.

Wind Speed Sensor. The HSM uses a constant current heated thermistor bead wind sensor. The HSM wind speed measurements should be equivalent to standard meteorological measurements for wind speeds between 0.5 and 6.5 m/sec but should also provide reasonable estimates of wind speed between 0.0 and 0.5 m/s. Because of the very high solar radiation levels characteristic of outdoor environments during summertime in the southern hemisphere there was concern that the exposed thermistor beads for the air temperature and wind speed sensors might absorb enough radiant energy to significantly bias the measurements. A removable solar radiation shield for the air temperature and wind speed sensors was fabricated to reduce the potentially degrading effects of high ambient solar loads on the accuracy of readings from these two sensors. The initial shield design strategy was to use a thin disk on top of the sensor mast to shade both sensors from overhead radiant loads and at the same time minimize interference with the horizontal air flow to the wind sensing thermistor bead. Figure 1 shows the HSM with its protective case open and the solar radiation shield in place on the wind speed /air temperature sensor mast. Figure 2 shows the sensors masts deployed without the solar shield.

Figure 1. HSM solar shield on.

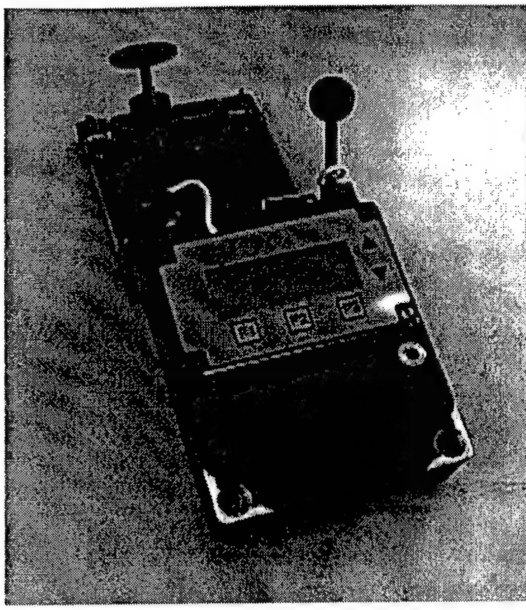
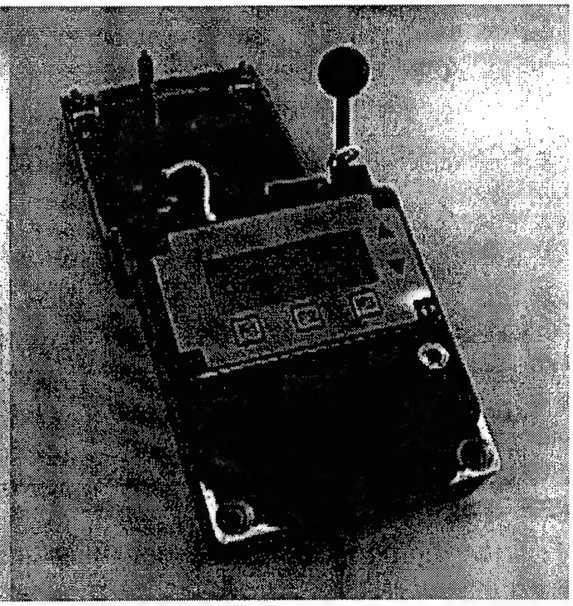


Figure 2. HSM solar shield off.



HSM PREDICTIVE MODEL VERIFICATION . At Barrow Island, in order to verify the HSM's predictive model implementation, we selected from a range of work rates (Light, Moderate, Heavy), clothing type (Shorts/T-shirt, Nomex-1 Piece, and BDU) , and acclimatization status (Yes, No) settings for the HSM inputs prior to each measurement cycle. These input settings thus included, but were not limited to, our best estimate of the work crew's clothing, work rate, and acclimatization status. Verification of HSM model implementation was accomplished by using the recorded HSM input settings and corresponding sensor readings for each HSM measurement cycle as inputs to the desktop computer implementation of the USARIEM heat strain model, and comparing the output results for work rest cycle and hourly water requirements.

STATISTICAL. Accuracy estimates were based on the difference, d, between the paired measurements (HSM sensor reading - reference instrument reading). The average difference, $\bar{d}$, and its standard deviation, $s_{\bar{d}}$, were computed in order to isolate random and systematic error components (Zar, 1984). Root Mean Square Error (RMSE) was also computed.

RESULTS

PRE-TEST CALIBRATION CHECKS AT USARIEM. Each HSM completed 3 measurement cycles in each of 4 test environments at a constant 50% RH: Air

temperatures of 25 and 35 ^{O}C, and wind speeds of 1.0 and 2.5 m/s. Results of chamber evaluations of the three HSM units, prototypes 1,3, and 4, prior to the Barrow Island field tests are shown in Table 2.

Table 2. Summary of results from four test environments in USARIEM laboratory chamber.

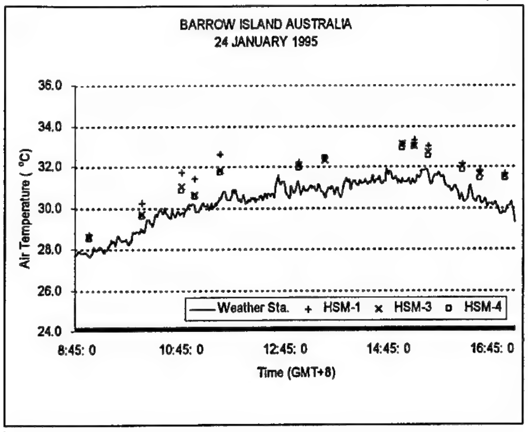
	Air Temp. ^{0}C			Humidity %			Wind Speed m/s			Black Globe ^{0}C		
HSM No.	1	3	4	1	3	4	1	3	4	1	3	4
Mean Error, $\bar{d}$	0.5	0.4	0.2	1.0	1.8	2.0	0.7	0.3	0.2	0.6	0.4	1.1
SD of $\bar{d}$, $s_{\bar{d}}$	0.1	0.1	0.2	1.7	1.8	1.9	0.2	0.1	0.1	0.3	0.2	0.2
RMSE	0.5	0.4	0.3	1.9	2.6	2.8	0.7	0.3	0.2	0.7	0.5	1.1

Sensor errors in the limited laboratory chamber environments were generally within required accuracy limits, although all sensors read higher than reference values. HSM-1 showed a systematic error in wind speed of 0.7 m/s too high, and HSM-4 showed a systematic error in the black globe temperature sensor reading of 1.1 °C too high. Because these checks were completed just prior to scheduled departure for Australia, the instruments were not returned to Southwest for recalibration. These data thus provide a limited but useful quantification of baseline sensor errors for evaluating sensor performance in the more complex outdoor and deep mine environments.

BARROW ISLAND. During the test period heat stress conditions at Barrow Island were, according to the resident staff, unusually moderate. The reference weather station-measured air temperatures ranged from 25 to 32 °C, relative humidities from 39 to 62% , wind speeds from 2 to 8 m/s and black globe temperatures from 27 to 42 °C.

<u>**HSM Sensor Performance**</u>. A total of 51 frames of HSM data were obtained during the 3.5 work days we spent at the well site. Three HSM prototypes, Nos. 1, 3, and 4, were tested at Barrow Island. The solar shields were in place on the HSM wind speed/air temperature sensor mast for 25 frames and removed for the remaining 26 frames. Solar shield effects on the wind speed and air temperature sensor readings were reflected in the output from the black globe size correction algorithm implemented in the HSM. In addition, the HSM air temperature measurements showed a fairly consistent high bias of about 1.3 °C. The relative humidity sensor on the HSM performed within the specified accuracy limits. Figures 3 and 4 illustrate HSM sensor performance relative to the one minute interval weather station recordings of air temperature, humidity, wind speed, and black globe temperatures on 24 January, the warmest test day. Solar shields were not in place on that day.

Figure 3. Air temperature and relative humidity plots.



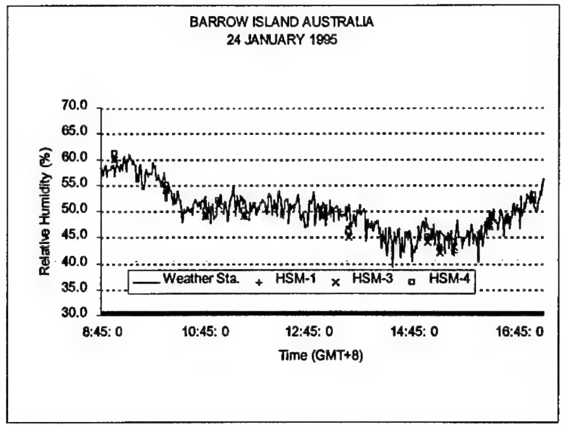
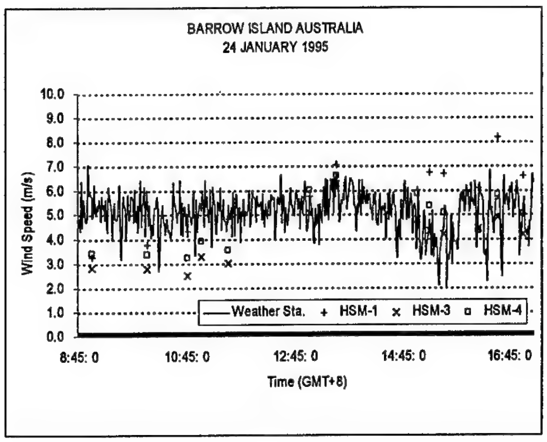


Figure 4. Wind speed and Black Globe temperature plots.



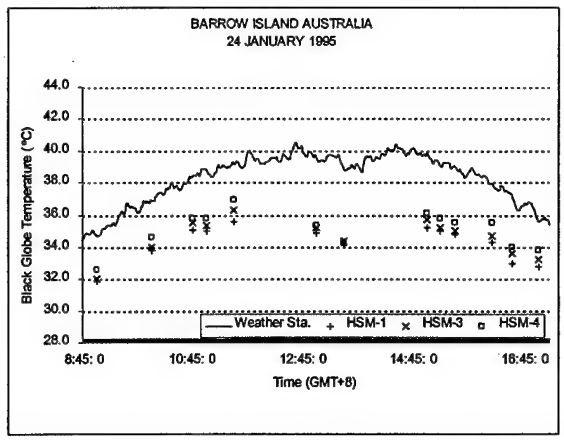


Table 3 provides a statistical summary of sensor measurement errors for each of the three prototypes over the full 3 day test period at Barrow Island. Negative values of $\bar{d}$ indicate HSM measurements lower than reference measurement. Clearly the wind speed and black globe temperature measurements differed substantially from the reference measurements made by the weather station. The algorithm used to correct the miniature black globe reading to a full size black globe value is referenced to the air temperature measurement. It is likely that the small but generally consistent high bias in the HSM air temperature measurement would account for some of the low bias in the HSM black globe readings.

Table 3. Statistical summary of sensor measurement errors for each of the three prototypes over the 3 day test period at Barrow Island.

	Air Temp. °C			Humidity %			Wind Speed m/s			Black Globe °C		
HSM No.	1	3	4	1	3	4	1	3	4	1	3	4
Solar Shield ON (n=25)												
Mean Error, $\bar{d}$	1.2	1.4	1.4	-0.9	-1.5	-0.7	1.2	1.1	1.3	-3.2	-3.4	-3.0
SD of $\bar{d}$, $s_{\bar{d}}$	0.3	0.4	0.3	1.3	1.7	1.7	1.3	1.2	1.2	0.6	0.6	0.7
RMSE	1.2	1.4	1.4	1.6	2.3	1.9	1.7	1.6	1.8	3.3	3.5	3.1
Solar Shield OFF (n=26)												
Mean Error, $\bar{d}$	2.0	1.3	1.3	-0.4	-0.9	0.0	0.7	-1.5	-0.7	-3.9	-3.3	-3.0
SD of $\bar{d}$, $s_{\bar{d}}$	0.9	0.5	0.6	1.8	2.2	1.9	1.6	0.8	0.8	1.5	1.2	1.4
RMSE	2.2	1.4	1.4	1.8	2.3	1.9	1.7	1.7	1.1	4.2	3.5	3.3
Combined (n=51)												
Mean Error, $\bar{d}$	1.6	1.3	1.3	-0.6	-1.2	-0.3	0.9	-0.2	0.2	-3.6	-3.4	-3.0
SD of $\bar{d}$, $s_{\bar{d}}$	0.8	0.4	0.5	1.6	2.0	1.8	1.4	1.6	1.4	1.2	0.9	1.1
RMSE	1.8	1.4	1.4	1.7	2.3	1.9	1.7	1.6	1.5	3.8	3.5	3.2

HSM Software Verification. The HSM model outputs were essentially identical to those obtained from the desktop computer implementation of the USARIEM Heat Strain model. For the 51 frames of data collected at Barrow Island, all work/rest cycle outputs agreed within $\pm$ 1 minute and the water requirements agreed within $\pm$ 0.1 quarts/hr.

MOUNT ISA MINES. A total of 8 frames of data were obtained at four locations underground. One Heat Stress Monitor , prototype number 4, was used. In the area known as the deep copper ore body which lies between 1,100 and 1,400 meters below ground, measured air temperatures at four locations ranged from 32 to 37 ^{O}C, with relative humidities between 23 and 41%. Air movement ranged from 0.5 to 1.8 m/s in the work spaces.

Sensor Performance. A summary of the limited results obtained at the deep mine locations are shown in Table 4. In general, the HSM sensor readings fell within the range of contemporary measurements obtained by the Mount Isa staff using a number of their standard environmental monitoring devices. In several cases, multiple measurements of a single parameter were obtained using different sensor technologies and instruments. Results for the HSM

sensor readings are therefore shown here in a quantitative context defined by one or two legitimate but not necessarily definitive reference measurements.

Table 4. Statistical summary of sensor measurement errors for HSM-4 at four deep mine locations at Mount Isa Mines.

In all cases, n = 8	Air Temp. °C		Humidity %		Wind Speed m/s		Black Globe °C
Reference Meas.:	Kano-max	Sling Psyc.	Kano-max	Sling Psyc.	Kano-max	Vane Anem.	Reuter Stokes Wibget
Mean Error, $\bar{d}$	-0.3	0.1	3.1	2.3	-0.2	0.1	0.1
SD of $\bar{d}$, $s_{\bar{d}}$	0.2	0.2	0.9	2.2	0.2	0.1	0.3
RMSE	0.4	0.3	3.3	3.2	0.3	0.1	0.3

DISCUSSION

DUAL USE REQUIREMENTS. Industrial heat stress environments in Australia pose significant technical challenges for an integrated sensor system development. The common technical requirements thread of the original military HSM persist in the need for accurate measurements from a small, rugged, light weight instrument. These factors necessarily constrain the choice of power supply, sensors, and their arrayment geometry. The overarching goal is therefore to develop an optimized sensor suite for use in environments where the measured parameters, ambient temperature, humidity, wind speed/air movement, external radiant load, and, in deep mine applications, atmospheric pressure all vary dynamically and independently across a potentially extensive domain. These tests provide a limited but useful evaluation of this prototype sensor suite in a controlled laboratory environment and two very different industrial workplace environments.

SENSOR ACCURACY METRICS. In interpreting the results shown in the preceding tables, it may be useful to briefly restate the analytical basis of the metrics involved. The overall accuracy estimate is the RMSE value and the metrics $\bar{d}$ and $s_{\bar{d}}$ allow us to separate and quantify the random and systematic error components. If the random error component, $s_{\bar{d}}$, is small, even a fairly large systematic error component, $\bar{d}$, can be easily corrected with a suitable calibration constant to improve the RMSE. On the other hand, if the random error component is large, its value my be taken as a fundamental limit of that sensor's performance potential.

Dependency. In evaluating the performance metrics for the HSM sensors, it is important to note that several of the HSM's output values are in fact dependent upon the accuracy of other measurements. An error, for example, in air temperature measurement, would propagate errors in the relative humidity and wind speed outputs . Errors in the wind speed and air temperature values used in the black globe correction algorithms would also result in an erroneous black globe temperature. From our results at Barrow Island it is clear that the improvement of wind speed sensor performance in outdoor settings is a priority concern.

MODIFICATIONS. Results indicate that a number of modifications need to be considered in order to make this device suitable for use in these industrial settings. These include sensor-related issues as well as predictive model applicability in the context of viable industrial heat stress management practices.

Sensors. Clearly the dynamic high wind speeds and solar loads at Barrow pushed the current sensor suite's response characteristics to the limit. From these data it appears likely that a redesign of the solar shielding for the air temperature and wind speed sensors would improve accuracy of the HSM's wind speed measurement as well as the black globe measurement which requires accurate wind speed and air temperature measurements for the size correction algorithm.

Predictive Model Applicability. While the USARIEM heat strain model with its focus on the work/rest cycle risk management approach is appropriate in above ground operations such as those at Barrow Island, that approach appears to have limited appeal in the production oriented mining workplace. This is in part because the below-ground operational paradigm is essentially based on balancing work-space cooling costs with safety and productivity. For the most part, the underground work space environment can be, and is, actively modified to optimize safety and productivity. The massive engineering and power costs of deep mine ventilation result in the reduced underground air temperatures and humidities and increased air movement that permit humans to function in what would otherwise be intolerable heat stress environments.

Additional System Requirements. A backlit display, calibration interfaces, and autonomous data logging capabilities were identified as crucial enhancements in this initial exposure of the HSM to industrial users. The consolidation of these requirements with Army requirements for a smaller and lighter physical unit, provides a significant opportunity to exploit the cost efficiencies of a shared research and development effort.

CONCLUSIONS

HSM CONCEPT. The HSM's integrated sensor suite, heat stress model, and simple user interface was conceptually attractive to occupational health managers at the Wapet facility on Barrow Island and at Mt. Isa Mines.

SENSORS. The sensor suite performed reasonably well with the exception of wind speed. The wind speed sensor clearly requires additional research, development, and engineering effort.

PREDICTIVE MODEL. The USARIEM Heat Strain model implemented in the HSM performed perfectly.

SYSTEM ENHANCEMENTS. It is clear that the industrial community requires substantial engineering enhancements including backlit display, calibration interfaces, and autonomous data logging capabilities. The scale of these enhancements suggests an extensive engineering re-design of HSM and would appropriately include reductions in weight and volume having high value to potential military users.

RECOMMENDATIONS

HIGH LEVEL DESIGN DOCUMENT. Develop a consolidated formal engineering document identifying key operational and functional requirements for an improved /miniaturized Heat Stress Monitor.

PROTOTYPE FABRICATION. Proceed with development of an improved HSM prototype based on the high level design document. First, initiate contract to fabricate an initial prototype improved/miniature HSM incorporating baseline sensor system, case, hardware, and firmware components sufficient to establish proof of concept. Second, implement incremental enhancements and identify low level design changes needed to achieve all high level design goals. Third, produce a sufficient number of these to allow a statistically valid assessment of system performance across a wide range of potential applications.

FOLLOW ON CRDA. Establish follow on CRDAs to maximize return on research and development investments focused on a production level miniature HSM with core functions suitable for both military and industrial applications.

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